THE NON-LINEAR RELATIONSHIP BETWEEN ROAD TRAFFIC EMISSIONS AND POLLUTANT CONCENTRATIONS

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INTRODUCTION

Air quality models for road traffic emissions have varying degrees of complexity depending on the application; the more basic models often assume a linear relationship between emissions and concentrations, thus ignoring non-linear near source effects. For example, one of the earliest stages in estimating concentrations using the UK highway authorities' air quality screening method in the Design Manual for Roads and Bridges (DMRB, 2003), is to estimate concentrations per unitary emission rate at the distance of interest, so the results are calculated by linearly proportioning the given concentration by the emission rate.

Concentrations predicted by linear models tend to compare well with monitored data for only a subset of road types. Boulter et al. (2003) found that a series of adjustment factors significantly improved correlations between monitored and modelled data for the initial DMRB calculations mentioned above, and these adjustment factors have been incorporated into the current version of the model. A number of relationships were investigated: road type, annual average daily traffic flow (AADT), speed and source-receptor distance. Obviously, some of these variables are not independent – a high traffic flow road quite often has a high speed, for example on a motorway. Boulter et al. found that the most accurate correlation resulted from applying AADT-dependent adjustment factors.

Figure 1 shows these factors for the 3 pollutants CO, NO_X and PM_{10}. Clearly, the factors are very different for each pollutant. For all pollutants, a constant, non-unity adjustment is applied for flows less than 15 000 AADT; for flows greater than this value, an exponentially decreasing factor is applied. These factors have a significant effect on concentrations – ranging from 3 for low flows, to 0.15 for high flows.

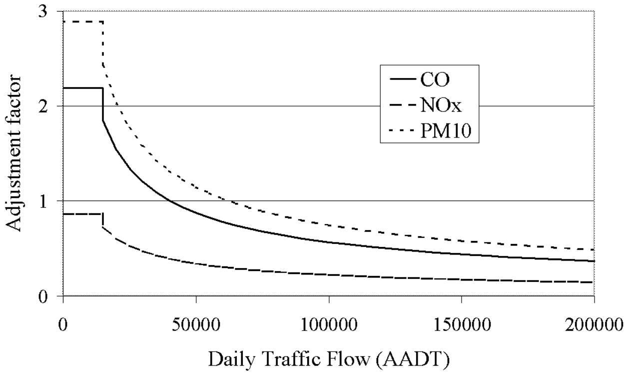

Figure 1 – Traffic-flow dependent adjustment factors applied in the Design Manual for Roads and Bridges (DMRB) Screening Method Version 1.02 (Boulter, 2003)

Although models that apply adjustments derived from monitored data seem to give relatively good results, they clearly have drawbacks. Specifically, correlations are biased towards the set of data from which they have been derived; the adjustments have to be recalculated every time the basic model is changed. In addition, with regard to the above example, the factors are different for each pollutant. When neglecting chemistry and deposition effects, dispersion of pollutants should be independent of pollutant type; this implies that the above correlations are attempting to represent more than just the effect of increased traffic flow. In order to improve linear models, it may be better to include the non-linear processes involved in the dispersion of pollutants in the near field. This paper discussed some of these processes, specifically: vehicle-induced turbulence, initial mixing height of emissions. There is also some discussion of resuspension of particulates.

VEHICLE-INDUCED TURBULENCE

Proposed formulation

For busy roads, the traffic volume generates additional turbulence. This means that average annual concentrations are lower in the vicinity of the road, due to increased plume spread across the road. The proposed formulation for this extra lateral plume spread, $\sigma_{y_{vehicle}}$, is as follows:

$$\sigma_{y_{vehicle}} = \sigma_{v_{vehicle}} t \left\{ 1 + \left(\frac{t}{t_d} \right)^2 \right\}^{-1/2} \qquad (2.1)$$

where the lateral turbulence term, $\sigma_{v_{vehicle}}$, is derived from that used to represent increased vertical turbulence in the OSPM street canyon model (Hertel and Berkowitcz, 1989):

$$\sigma_{v_{vehicle}} = b \left(\frac{N_H U_H A_H + N_L U_L A_L}{W} \right)^{1/2} . \qquad (2.2)$$

The turbulence decay time, t_d, is given by

$$t_d = \left(\frac{W}{\tau} \right) / \sigma_{v_{vehicle}} . \qquad (2.3)$$

In the above definitions, t is the road-receptor travel time in seconds, W is the road width (m), N_L, U_L and A_L are the number per second, speed (m/s) and cross-sectional area (m^2) of light vehicles respectively; N_H, U_H and A_H are the corresponding variables for heavy vehicles. The constant b is taken to be 0.3, as in the OSPM model, and the value for the constant τ, which represents the decay in the far field, should be derived by model comparisons with monitor data. Equation (2.1) represents 2 regimes. In the near field, when $t << 1$, $\sigma_{y_{vehicle}} \to \sigma_{v_{vehicle}} t$ i.e. the plume spread term is dominated by the increased lateral turbulence generated by the traffic. In the far field, when $t \to \infty$, $\sigma_{y_{vehicle}} \to W / \tau$ i.e. the plume spread term becomes independent of the speed and number of vehicles on the road, and is just dependent on the road width. Note that the vehicle induced turbulence considered by, for example, Di Sabatino et al. (2002) is for street canyons where the additional turbulence is mainly confined within a finite volume; this is not the case for an open road discussed herein.

Wind-direction dependence

The vehicle-induced turbulence formulation above has most effect when the wind direction is near to parallel to the road, and least effect when the wind direction is perpendicular to the road. Figure 2 shows why this is the case.

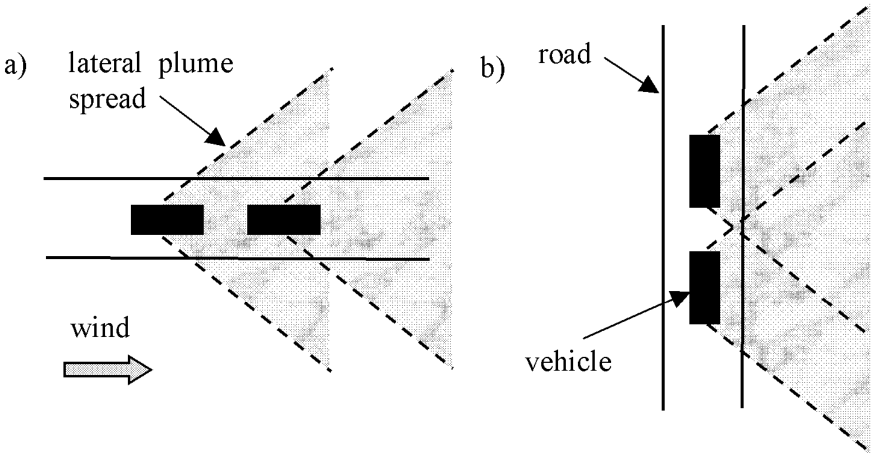

Figure 2 – Diagrams showing lateral plume dispersion from vehicles when the road is a) parallel, and b) perpendicular to the to the prevailing wind direction

When the wind parallel to the road, as shown in Figure 2 a), the plume spreads out laterally, and when there are more vehicles, or the vehicles are travelling at higher speeds, turbulence will be increased and pollutants will be dispersed further from the roads. Conversely, when the wind is perpendicular to the road, lateral dispersion will also be increased for higher flows and speeds, neighbouring plumes will always overlap, thus negating any decrease in concentrations due to increased dispersion.

Results

The formulation presented above has been included in the air dispersion model, ADMS-Urban (2005). The constant τ has been given a value of 0.1, which was chosen after a validation exercise. The areas of the light and heavy vehicles (variables A_L and A_H in equation (2.2)) are taken to be 4 and 16m² respectively. Figure 3 shows some example annual average concentrations, normalised by emission rate, for different vehicle flows, with the low, medium and high rates corresponding to 10 000, 50 000 and 240 000 vehicles per day respectively. This plot shows that concentrations in and close to the road are reduced by some 15% by the highest flows relative to the lowest flows. A similar pattern of results is seen when speed variations are considered for a fixed flow rate i.e. higher vehicle speeds result in relatively lower concentrations than lower vehicles speeds.

INITIAL MIXING HEIGHT

Proposed formulation

Roads are usually modelled as line sources. The height of the source should represent the location at which the pollutants are emitted, and for light and heavy vehicles, this is often different. In addition, larger vehicles produce more turbulence than light vehicles. These combined effects mean that a road for instance with 95% light, 5% heavy vehicles will produce different ground level concentrations to one with 80% light and 20% heavy vehicles with comparable emissions.

Light vehicles are a mixture of cars (height usually <1m) and light goods vehicles (height usually>1m). They all have low level exhausts (30-45cm); an intermediate value of 1m is proposed as an initial mixing height for these vehicles. Heavy vehicles are a mixture of buses and lorries. In the UK, depending on road type/location, between 6 and 20% of the heavy fleet have vertical, high level exhausts; the remainder have exhausts at the same level as light vehicles.

Exhausts have an exit velocity of between 15 and 20m/s (54-72km/hr). At low speeds, the vertical, high-level exhausts have a high source height, corresponding to a relatively high initial mixing height, perhaps 3m. At higher speeds, the effect of the turbulence created by the moving vehicle dominates the flow, and the emissions will be well mixed over the height of the vehicle.

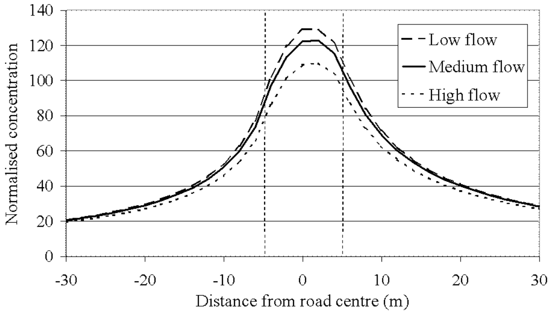

Figure 3 - Annual average concentrations normalised by emission rate for different traffic flows (road width = 10m, indicated by vertical dashed lines, roughness = 0.2m, speed = 110 km/kr)

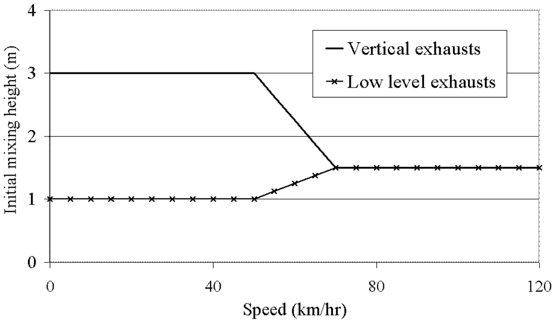

Figure 4 – Proposed variation of initial mixing height parameter with speed for light and heavy vehicles.

For the heavy vehicles with low level exhausts, the initial mixing height for low speeds can be assumed to be the same as that for light vehicles; at higher speeds, as described above, the emissions will be well mixed over the height of the vehicle, and therefore the initial mixing height would be bigger, perhaps 1.5m. Consequently, the initial mixing height for heavy vehicles is speed dependent. Figure 4 shows the proposed variation of initial mixing height with speed for heavy vehicles with low and high level exhausts. It has been assumed that there is a transition region where the influence of the height of the exhaust on initial mixing height (dominant for low speeds) is replaced by the effect of the height of the vehicle on initial mixing height (dominant for high speeds). This transition region is taken to be between 50 and 70km/hr, where the speed of the exhaust is of the same order of magnitude as the speed of the vehicle.

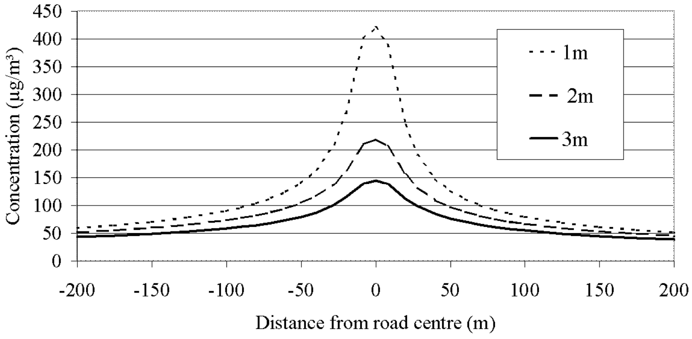

Figure 5 – Variation of annual average concentrations with initial mixing height for a 30m wide road

Results

The ADMS-Urban model includes a parameter, known as the initial mixing height, which specifies the height of the source, and adjusts the initial vertical plume spread parameter. Figure 5 shows the variation of annual average concentrations with initial mixing heights of 1m, 2m and 3m, for a 30m wide road with a relatively high traffic flow. This plot shows that varying the initial mixing height of the source has a significant effect on concentrations. Specifically, at the road centre, concentrations are decreased by 50% and nearly 200% for heights of 2m and 3m relative to a 1m mixing height (the latter being the current default for all sources in the ADMS-Urban model).

PARTICLE RESUSPENSION

In Figure 1, the adjustment factors for PM_{10} are greater than those required for CO and NO_x. This is likely to reflect the fact that some emissions not related to road traffic are not accounted for in the emissions factors for vehicles. The most important of these sources is likely to be resuspension. For example, a comparison between particle concentrations near a busy street canyon (Marylebone Road) and an urban background site (Bloomsbury) in London showed that at the former site the concentration of the PM_{10} particles in the size range greater than 2.5pw was substantially higher (Harrison et al. 2001); this was attributed to resuspension. A parameterisation of these emissions is currently being developed.

SUMMARY

The paper has detailed the impact of vehicle induced turbulence and vehicle exhaust location on dispersion of traffic emissions in the near field. These processes account for some of the non-linearities observed between vehicle flow rate and pollutant concentrations. Other near source processes such as non-exhaust emissions are currently being studied.

ACKNOWLEDGEMENTS

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